Single-Trial Analysis of V1 Responses Suggests Two Transmission States

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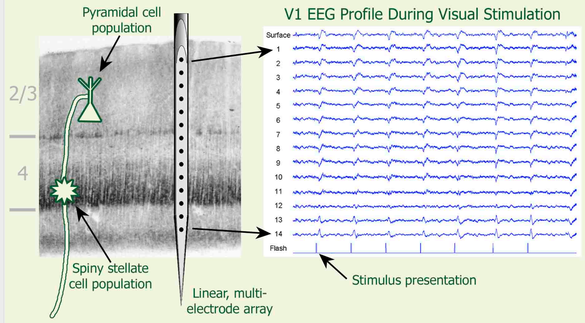
Abstract

Sensory processing in the visual, auditory, and somatosensory systems is often studied by recording electrical activity in response to a stimulus of interest. Typically, multiple trial responses to the stimulus are averaged to isolate the stereotypic response from noise. However, averaging ignores dynamic variability in the neuronal response, which is potentially critical to understanding stimulus-processing schemes. Thus, we developed the multiple component, Event-Related Potential (mcERP) model [Knuth et al., Dyn. Neuro. X 2002; Knuth et al., SFN 2002]. This model asserts that multiple components, defined as stereotypic waveforms, comprise the stimulus-evoked response and that these components may vary in amplitude and latency from trial to trial. Application of this model to data recorded simultaneously from all six laminae of V1 in an awake, behaving monkey performing a visual discrimination yielded three components. The first component localized to granular V1, the second was located in supragranular V1, and the final component displayed a multi-laminar distribution. Estimates of the single-trial responses were reconstructed using these model components and their trial-specific amplitudes and latencies. Single-trial onset latencies of this estimated response were shorter in granular V1 than in supragranular V1. This finding is consistent both with the average response and with the anatomical evidence that suggests feedforward input to V1 enters the granular layer and progresses to supragranular layers. In addition, the granular component of the model displayed several interesting trial-to-trial characteristics including (1) a bimodal latency distribution, (2) a latency-related variation in response amplitude, (3) a latency correlation with the supragranular component, and (4) an amplitude and latency association with the multi-laminar component. Direct analysis of actual single-trial data from granular V1 also revealed this bimodal latency distribution. The bimodal latency distribution of the granular component and its associated findings suggest that V1 has at least 2 transmission states, which may be modulated by various effects such as attention, dynamics in local EEG rhythm, or variation in sensory inputs.

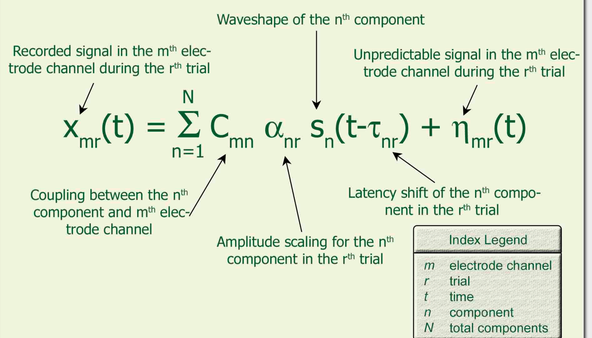
Why Single Trials?

A sensory stimulus activates multiple neuronal ensembles whose electrical activity can be measured. Activation of these ensembles exhibits trial-to-trial variability, which when characterized reveals a "higher resolution picture" of sensory processing schema. For example, the V1 feedforward circuit model states that visual input enters layer 4C at a precise latency and progresses to layers 2/3. Trial-to-trial co-variation in activity from these two layers is thus expected. Deviations in onset latency and amplitude might signal multiple activation states related to different task or subject conditions. In addition, deviations in trial-to-trial co-variation of activated layers would indicate the existence of different processing schemes. Dynamics such as these can only be studied in single-trial data.



The mcERP Model

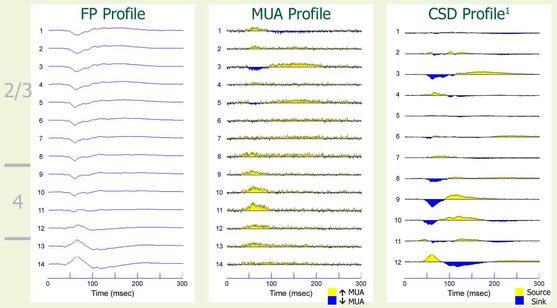
The mcERP model defines multiple components as stereotypical waveshapes that may vary in amplitude and latency from trial to trial. This is expressed mathematically as:



Bayes' theorem is applied to compute the posterior probability of the model from which *maximum a posteriori* (MAP) solutions are estimated using a fixed-point algorithm.

Experimental Paradigm

A linear, multi-electrode array was inserted acutely into macaque V1 as illustrated earlier. The subject performed a visual discrimination task during which field potential (FP) and multiunit activity (MUA) were recorded. One hundred and seventy one responses to the non-target stimulus were averaged (see below).



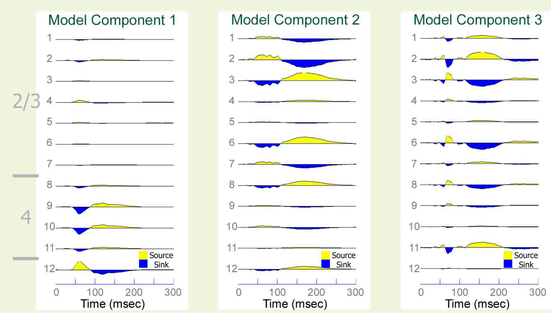
[1]Current source density (CSD) indicates the direction and magnitude of transmembrane current flow, which is responsible for generating field potential (FP) and sometimes MUA. The CSD is approximated as the second spatial derivative of the FP.

The CSD profiles show that earliest onset of activity is a sink in layer 4C (CSD channel 10). This sink and the corrresponding increase in MUA (MUA channel 11) indicates excitation and represents thalamic input into layer 4C. Also, the onset latencies of the supragranular layers (eg. sink/source configuration in CSD channels 3 & 4) is later than that in layer 4C as predicted by anatomical data.

For information about mcERP, please visit Knuth *et al*.
SFN posters 506.4 and 506.5 show mcERP vs ICA and application to more data.

Modeling Results

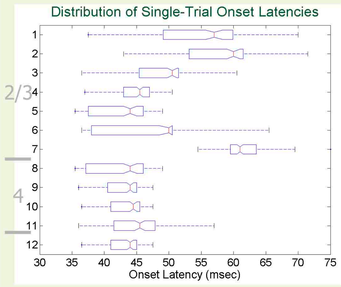
The mcERP model was applied to single-trial FP data resulting in estimates of three component waveshapes and their associated spatial locations and single-trial amplitudes and latencies. Below are CSD maps of the model components.



Model component 1 (MC1) - layer 4C activation by thalamic inputs
Model component 2 (MC2) - layer 4C projection to supragranular layers
Model component 3 (MC3) - multilaminar component similar to a feedback profile

The single-trial parameters of each component are presented later...

Verifying Feedforward Circuitry



The Estimated Evoked Response (EER) in a single channel during a single trial was calculated as follows:

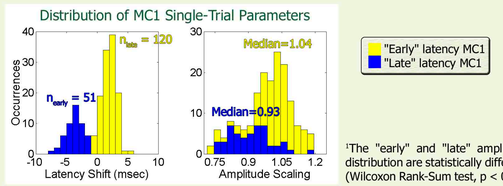
$$EER_{mr}(t) = \sum_{n=1}^{N} C_{mn}\ \alpha_{nr}\ s_n(t-\tau_{nr})$$

The onset latency[1] of the EER was calculated for each channel during each trial. These single-trial distributions are consistent with the V1 feedforward circuit model.

[1]Calculated as the first point where the absolute amplitude of the EER exceeded 5 SD above the baseline (0-35ms) for 8 ms.

Bimodal Activation of Layer 4C

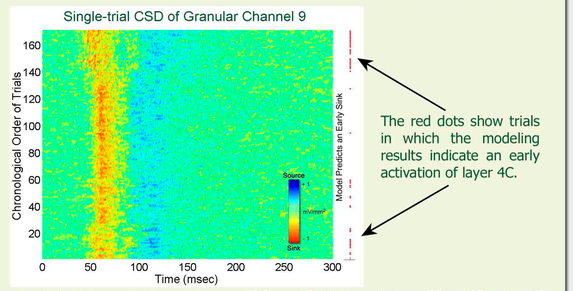
Since the model permits trial-to-trial latency and amplitude variability, we can examine these dynamics to characterize activation patterns in different laminae. The initial activation of layer 4C, MC1, illustrates a bimodal latency distribution. Furthermore, "early" activation is associated with smaller amplitude responses, and "late" activation is associated with larger responses. Note that the overall amplitude variability is small (variance = 0.011).



[1]The "early" and "late" amplitude distribution are statistically different (Wilcoxon Rank-Sum test, $p < 0.01$)

Verifying the Model in Layer 4C

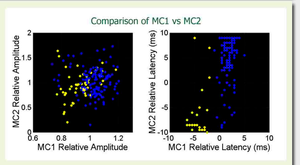
To verify the modeling results, we examined single-trial data from channel 9. The plot shows that the layer 4 sink usually begins at ~50 ms and occasionally onsets at a shorter latency (eg. trials 140-171). Estimating these latencies by a cross-correlation[1] method also illustrated a skewed bimodal distribution of onset.



[1]Cross correlation between the average response of Channel 9 (windowed between 25 and 95 ms) and the single-trial data was utilized to estimate the latency of this initial sink. These results are not shown here.

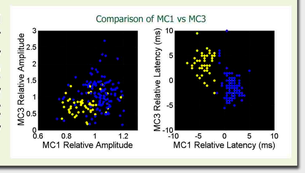
Component Co-Variation

The V1 feedforward circuit model suggests that layer 4C activation drives supragranular activation. Comparing MC1 and MC2, we observe that the onset latencies co-vary; however the amplitudes do not.



Yellow markers indicate trials during which "early" activation of MC1 occurred, and blue markers indicate trials during which "late" activation of MC1 occurred.

MC3 has a multilaminar distribution and an onset latency later than MC1 or MC2, and so we hypothesize that it may be a feedback component. MC1 and MC2 amplitudes and latencies both co-vary and may indicate that the layer 4C component influences feedback activity into V1.



Discussion

The mcERP model isolated three components and their single-trial variability. Co-variation of the single-trial parameters among the components followed expectations of previous anatomical and electrophysiological evidence. However, mcERP revealed a bimodal activation of layer 4C, suggesting that two transmission states exist. Model results and single-trial data illustrate that these two states occur in groups of trials and are rarely interspersed. Given this evidence, these transmission states may be related to eye position and attention but probably not phase of local EEG rhythm. Minute variations in eye position may manifest as slow drifts across the eye position window and therefore may cause a rare transition from one state to another. Attention related to expectation of an award would cause interspersed transitions between the states, but global modulation of attentional levels may induce shifts during blocks of trials. Finally, the phase of the local EEG rhythm may affect transmission through V1, but we would expect random transitions since the phase ongoing activity should be uniformly distributed. Each of these possibilities will be explored to better understand the relationship between the layer 4C, supragranular, and multilaminar activations.

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